TRANSMISSION LINES; VOLUME INDICATORS; MONITORS

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Transmission Lines, Volume Indicators, Monitors

TRANSMISSION LINES

With increasing use of long distance telephone transmission lines for interconnecting widely separated broadcasting stations into networks of even national scope, the interest of the radio technician invades the field of telephone engineering. Owing to the rapid growth of public address systems and sound picture recording where voice frequency currents may be transferred over considerable distances, and because of the use of R.F. transmission lines in transmitters, the transmission line assumes an important position and you should have at least a speaking knowledge of this rather complex phase of Radio.

Broadly speaking, the principal problem is as follows: A

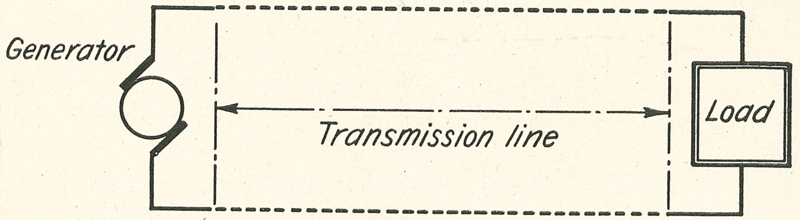


Fig. 1

generator of audio or radio frequency currents is to supply electrical energy to a distant load, the two being connected by an overland transmission line as represented in Fig. 1. A transmission line of this sort is said to be a "balanced" line when both of the conducting wires are equally distant from the ground while it becomes an "unbalanced" line if the two conducting paths are not symmetrical with respect to ground.

We are concerned primarily with the loss or attenuation which such a transmission line offers to the signals as a whole (intensity attenuation) and with the relative attenuation which the different audio frequencies suffer in passing over the line when the signal contains a band of frequencies (frequency attenuation or distortion). A detailed study of this problem requires an advanced mathematical analysis, beyond the scope of this text, and beyond the scope of the ordinary engineer. Yet this subject is so important in sound and R.F. transmission that our

course would be incomplete without giving it some consideration. A simple treatment will suffice here to explain some of the fundamental concepts of the problem and to acquaint you in a general way with some of the principal terms and phenomena involved. Do not feel disheartened if you find the subject hard going. And it will be wise not to question the derivation of the equations given as they could not be explained without the use of complex mathematics.

Before we go into the subject of line transmission, let us first inspect the services and frequencies that are to be met with in practice. The different forms of electrical communication over wire and cable circuits and their frequency requirements are as follows:

Telegraph communication, in which signalling is done by opening and closing a direct current circuit by means of a keying system, covering a range of frequency up to about 100 cycles per second. The frequency is of course determined by the speed of keying.

Carrier current telegraphy, wherein Morse signals are modulated upon a sinusoidal carrier frequency somewhat like an R.F. current modulated with voice current. In this way a number of independent communications may be carried on over a single circuit. If communication is carried on over a cable system, the carrier frequencies lie between the limits of about 400 and 5,000 cycles per second; while over open wire lines it is common practice to use a range of carrier frequencies from 3500 to 12,000 cycles per second.

Telephone communication of the ordinary or "message" sort. This will be quite satisfactory if the circuits and equipment are capable of transmitting a voice frequency range from approximately 250 to 3000 cycles per second.

Carrier telephony. In this service it is general practice to modulate the signals on carrier frequencies ranging from 5000 to 50,000 cycles per second, which makes possible about six voice channels, 6000 cycles wide, within this range.

Musical program transmission. For the highest grade program transmission over a broadcasting network which must carry, in addition to the human voice, both higher and lower frequencies which form important parts of instrumental music, efforts are made to procure a uniform undistorted transmission over a range of from 40 to 8000 cycles per second. To meet these more rigid requirements, land lines, repeaters, etc., used

in broadcasting networks have to be more carefully assembled and balanced than in the case of telephone lines which are used merely for message telephony. Occasionally facilities for these high grade lines are lacking so that the musical programs, if of high calibre, suffer a certain amount of frequency distortion.

To complete the picture we shall note that in *radio communication* by means of electromagnetic waves radiated into space without the restriction of wire circuits, the so-called *long wave radio* covers a range of from 12 to 550 kilocycles per second. R.F. currents are also sent over transmission lines, the purpose being to connect with the least possible loss or radiation, two remote parts of the R.F. system. The regular *broadcast band* covers a range from 550 to 1500 kilocycles per second while *short wave communication* is carried on beyond 1500 kilocycles per second. At the present time considerable research work is

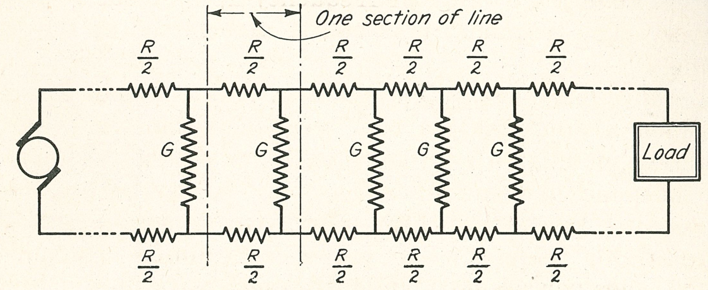


Fig. 2

being carried on in the range of *ultra short waves* or "quasi-optical" waves having frequencies of several hundred megacycles per second.

Let us consider a telephone transmission line carrying very low frequencies so that the reactance of the line (due to inductance or capacity) will be quite negligible compared to its resistance. Such a simple uniform transmission line is a pair of "open" (two wires in the air, spaced from each other) telephone wires. It would have a certain amount of series resistance represented by R (in Fig. 2), measured in ohms per unit length of the line. This resistance is, of course, determined by the conductivity and the size of the wires, and for a balanced line it is divided equally between the two wires. There will also be, in addition to the series resistance of the line, a certain amount of parallel conductance per unit length of the line. This is always called the leakage conductance which may be represented by G

and is measured in mhos; that is, reciprocal ohms between the two conducting wires. This conductance, in the case of an open wire line, is due chiefly to the leakage between the wires at the supporting insulators. It increases appreciably in wet weather.

If the values of these two quantities, R and G,* are known we may define certain properties of the line which play an important part in the behavior of the line. One is the so-called "surge resistance" † of the line, which is obtained by dividing R by G and then finding the square root, or in equation form:

$$R_o = \sqrt{\frac{R}{G}} \qquad (1)$$

Surge impedance is measured in ohms and as will be seen from

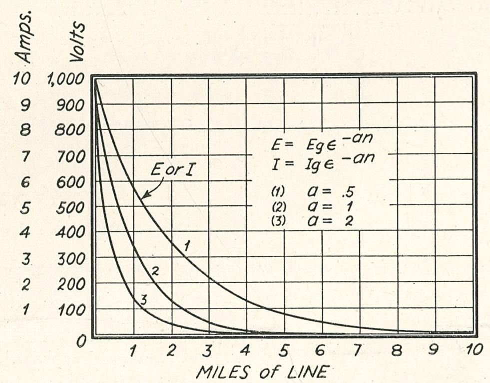


Fig. 3

the equation, is independent of the length of the line, that is, it depends only on the relative proportions of R and G.

Knowing R and G, we may also define another fundamental property of a unit length of transmission line, namely, the attenuation constant (factor) † per unit length of the line which is calculated from the formula:

$$a = \sqrt{RG} \qquad (2)$$

This attenuation constant determines how much the current and voltage are diminished as we go out along the line from the generator. If E_g represents the voltage across the terminals of the

* Ohms or mhos *per mile* of transmission, or *per foot*, etc.

† Surge resistance and attenuation factor are properties of the line and are as important as resistance, inductance and capacity in a simple circuit.

generator and I_g the current leaving the generator, the voltage and current, E and I, at any distance n * units of length away from the generator are graphically shown in Fig. 3. The horizontal lines represent miles of line, the vertical lines represent the current and voltage. The current and voltage drop off as these values are measured farther along the line, as we would expect. If the attenuation constant is increased, which we can see from equation (*2*) would be realized if R or G or both were increased, curves *2* and *3* in Fig. 3 would represent the new state of affairs. Notice, however, that the voltage and current in each case are the same at the generator terminals.

Examining further the curves shown in Fig. 3, it is easy to see that the attenuation of current and voltage is not uniform (linear). That is, doubling the length of the line will not cut the voltage and current in half, but will reduce them as shown

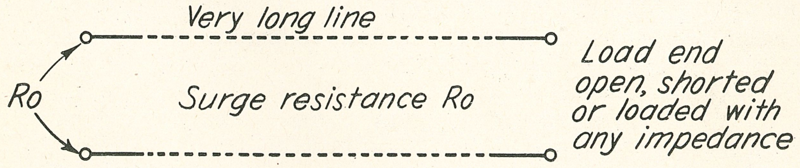


Fig. 4

by the curves in Fig. 3. These curves also show us that the higher the attenuation factor the more rapid will be the decrease in voltage and current. Thus it is obvious from formula (*2*) that for least attenuation, the line leakage and resistance should be as small as possible. Another thing that is important: No matter how long the uniform line may be, the current and voltage can never be reduced entirely to zero; that is, there will always be some energy arriving at the load end.

If a long uniform non-reactive line † is measured at either the load or the generator end, it will show a resistance of R_o ohms which is the surge resistance. This would be true no matter what the resistance of the load at the far end of the line may be. It might be any impedance from zero up to a value equal to an open circuit. See Fig. 4. In this case the source

* Miles of line.

† By a long open wire line we mean one more than about thirty miles long. A 2 mile line would be a short line. The terms "long" and "short," however, are relative terms; there is no definite dividing point between a long and a short line.

and load impedances are matched to the line without regard to the conditions at the other end.

If, on the other hand, a comparatively short uniform line of which the surge resistance is R_o, is measured at either extremity, it will show an actual resistance of R_o ohms only when the other end of the line is directly closed by a resistance of R_o ohms. See Fig. 5. This condition is representative of practical conditions as most lines are not long. If the load were any other value, the measured resistance at the other end would be quite different and as you know from your previous study, there would be a reflection loss. It is in view of these facts that we must "match" the generator and load to the line if we wish to obtain a maximum transfer of energy from the generator out into the line and subsequently from the line into the load. This question will be considered in detail later.

The transmission lines just discussed are ideal. They were taken up first because of their simplicity. It is difficult to transfer radio frequency or audio frequency currents without a line

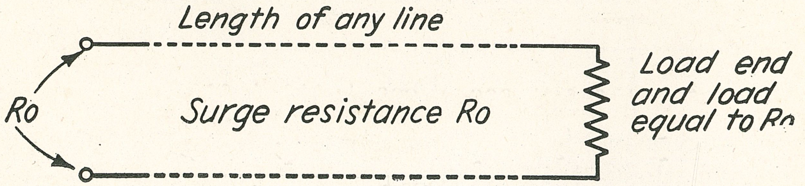


FIG. 5

showing inductance and capacity effects. But from an audio transmission point of view, a non-reactive line that approaches the ideal lines described is necessary if we wish to avoid frequency distortion. It is possible to design a reactive line so that it will behave as a non-reactive transmission system. Or we can load a line by inserting "loading coils," inductances, so as to accomplish the same effect.

We are now ready to consider transmission lines that carry higher frequencies so that the capacity and inductance associated with the lines cannot be neglected. Here the surge impedance, not the surge resistance, is the important factor. We will first consider open wire lines, in which the resistance R and the conductance G are made negligible in comparison to the capacity and inductance of the line by "loading" and there

remain only the distributed inductance and capacity as represented in Fig. 6. In this case the surge impedance, represented by Z_o, is:

$$Z_o = \sqrt{\frac{L}{C}} \tag{3}$$

where L is the distributed inductance per unit of length.
C is the distributed capacity per unit of length.

Notice that the surge impedance in this case is independent of the frequency of the line and depends solely on the line construction. This formula is so important that it is worth memor-

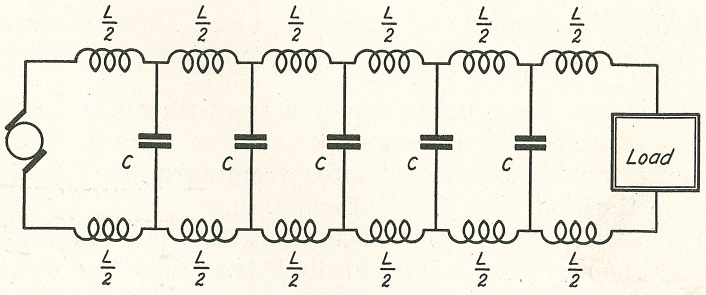


FIG. 6

$Z_o = \sqrt{\frac{L}{C}}$

izing. If the line is very long, the impedance measured at the generator or load end, regardless of what is at the other end, will be Z_o. On the other hand, if a short line with a surge impedance of Z_o is terminated with a load impedance equal to Z_o, the impedance measured at the other end is Z_o and the maximum current and voltage will be forwarded to the load, that is, there will be no reflection loss.*

Where transmission lines consist only of normal gauge wires, the inductance L, the line resistance R, the leakage factor G, and the capacity C must be considered. All these factors are represented in Fig. 7.

In an actual line of this kind, the surge impedance and the

*When the surge impedance of any line length is not known it may be obtained by measuring the impedance at the generator end when the load end is open (Z_{NL}), and with a load (Z_L), from the formula $Z_o = \sqrt{Z_{NL} \times Z_L}$.

attenuation constant depend also on frequency.* Consequently, matching of the source to the line or the *sink* to the line is possible at only one frequency. For all other frequencies, there will be reflection losses unless the line is loaded by making L and C so large that R and G are negligible.

Now you might well ask how the values of C and L for a unit length are determined. In open lines they must be calculated, but for convenience this information has been worked out for you and is given in the table below. If a pair of wires having a diameter of d (cm. or in.) and D in the same unit of measurement is the distance between the wires, measuring from their centers, a mile of transmission line would have an inductance in henries as given by the following table:

MILES OF OPEN LINE WIRE

D/d	L (Henries)	C (Microfarads)	Z_0 (Ohms)
40	0.00298	0.01022	540
50	0.00313	0.00971	567
60	0.00324	0.00935	589
70	0.00334	0.00905	606

These facts have been computed from formulas for the inductance and capacity of single mile units of various open lines. The surge impedance as calculated from formula 3 is also included in the table for your information.

From this data it will be seen that the surge impedance of ordinary open wire lines is generally between 500 and 600 ohms. Terminal apparatus at either end should accordingly be matched to this value if we wish to avoid reflection losses.

The formulas for the computation of the inductance and capacity of shielded and unshielded cables are quite complicated. We may note, however, that a standard No. 19 gauge cable having an inductance of one millihenry and a capacity of 0.076 microfarad per mile shows a surge impedance of 475 ohms at a

* The formula for Z_0 is $\sqrt{\frac{R + j2\pi fL}{G + j2\pi fC}}$ (the factor j signifies that R and $2\pi fL$ are 90° out of phase). It should be clear that if $2\pi fL$ and $2\pi fC$ are very small compared to R and G we obtain formula 1. If R and G are small compared to $2\pi fL$ and $2\pi fC$ we get formula 3 for Z_0. In many lines where G is small, loading coils are placed regularly in the line so as to make L large compared to R and Z_0 is found by formula 3. Then the line characteristic is independent of frequency. If $2\pi fL$ and G are negligible then $Z_0 = \sqrt{\frac{R_0}{2\pi fC}}$ and this condition is true for cables. Notice that frequency is involved and these lines may distort the signals unless specially loaded or equalized. We should mention that the basic formula for Z_0 takes into account the *propagation* factor which includes the *attenuation factor* and *phase angle.*

frequency of 800 cycles. Notice now that the frequency to be transmitted must be considered.

Because of L and C in a transmission line, the speed of voltage and current over the line is less than 186,000 miles per second. Thus the current in a line not only decreases in intensity but suffers a time lag T which can be determined, in seconds per unit length, from the equation:

$$T = \sqrt{LC} \tag{4}$$

On long lines this time lag becomes an appreciable quantity and gives rise to the phenomenon of electrical echo.

It was pointed out earlier in this chapter that a transmission line having only distributed leakage and line resistance, although decreasing the power delivered at the load end would not introduce frequency distortion. But suppose we have a trans-

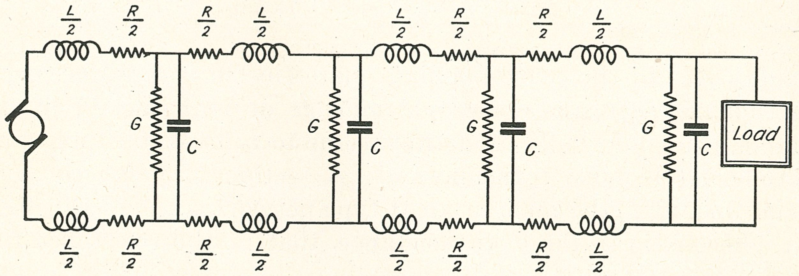


FIG. 7

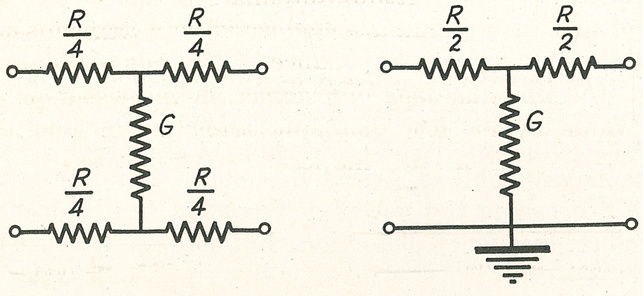
mission line as shown in Fig. 7 with distributed R, G, L and C. Engineers are able to adjust lines of this sort by *loading* them (inserting leaks, capacities and inductances) so that a so-called distortionless line can be obtained. It has been deduced from advanced mathematical analysis that when the ratio of inductance to resistance is equal to the ratio of capacity to conductance, this condition will be realized. Of course, we mean inductance or capacity for a unit length of line, usually a mile in length. Stated as an equation this appears as:

$$\frac{L}{R} = \frac{C}{G} \tag{5}$$

The attenuation constant will be the same as in a pure resistance line and the attenuation of current and voltage will be as represented in Fig. 3.

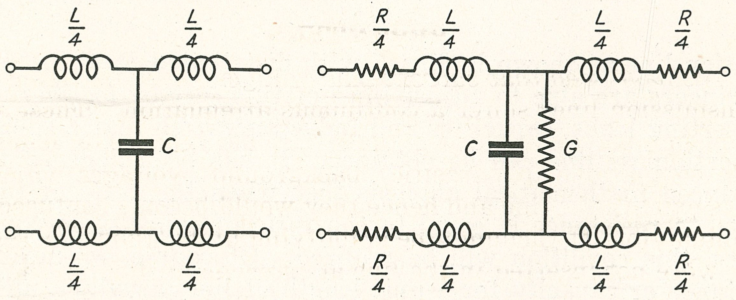
It should be mentioned at this point that *artificial transmis-*

sion lines are used extensively in laboratories for the purpose of studying transmission problems for it would be impracticable to test lines and devices connected to lines by attempting to build a transmission line 20 to 30 miles long. Such artificial lines take the form of electrical networks or circuits of a symmetrical nature wherein the series and shunt resistance elements are



a FIG. 8 b

made equal to the corresponding quantities in a real line, each section representing a specified mileage of real line. For example, you could build an artificial line to represent 10 miles of standard telephone transmission. A section of *balanced* artificial line takes the form of an H-type network as shown in Fig. 8a where R is in the loop resistance, that is, the resistance for



c FIG. 8 d

10 miles of double wire. Therefore, in making an H line, each section would have one-fourth the loop resistance or $R/4$, as in Fig. 8a. A section of *unbalanced* line having a common or ground side may be constructed in the form of a T-type network (see Fig. 8b). In this manner artificial lines of any length may be assembled for testing and study. Artificial lines may be constructed with any type of impedance in each arm,

and to conform to any of the more complicated lines, as in Figs. 8c and 8d.

We should not close our study of transmission lines without stating that knowledge of transmission phenomena has led to the development of multi-receiver operation on a single antenna. The R.F. transmission line is of importance in broadcast and commercial radio transmitting antenna systems where the R.F. generator and the antenna are connected by a transmission line. In this case, if the surge impedance of the line is known by calculation, the antenna load impedance is increased or reduced to this value by an R.F. coupling transformer and the R.F. energy is transferred with the least reflection loss.

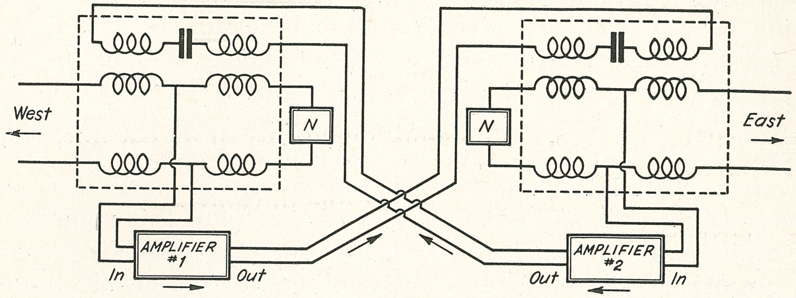


FIG. 9

REPEATERS

We have seen that current and voltage waves traveling over transmission lines suffer a continuous attenuation. These voice frequency waves would eventually become reduced to a magnitude comparable to parasitic "background" voltages which always exist in the line and hence they would become confused and unintelligible, if vacuum tube amplifying units, known as repeaters, were not inserted in the line at intervals to step up the level of transmission and thus maintain a sufficiently high signal-to-noise ratio. Since the noise level is approximately constant at any point in the line, it is evident that these amplifiers should be distributed along the line rather than located only at the terminals.

The vacuum tube amplifier is essentially a one-way device. That is, a signal must proceed from the grid to the plate. Thus if a two-way communication is to be carried on over a single line, a two-way repeater (represented schematically in Fig. 9)

must be employed. It will suffice to point out that the east-bound signals are amplified by amplifier No. *1* and the west-bound signals are amplified separately by amplifier No. *2*. East and west lines are each terminated through a so-called "hybrid" transformer * (shown inside the dotted lines) and a balancing network, *N*. The balancing network must be matched to the line and must also be made perfectly symmetrical in order to prevent "singing."

TRANSMISSION LEVELS

The transmission of speech currents over long land lines must be maintained at such levels as to insure no appreciable interference from the background noise which always exists in such lines. It has been found in general practice that the minimum level of ordinary telephone signals should be maintained at least 10 decibels above the background noise; that for picture transmission, such as telephoto, a difference of 15 decibels is desirable; that for the best quality broadcasting the minimum signal level should be from 20 to 25 decibels above the background. This latter difference is not always realized, although always aimed at. A high signal-to-noise ratio of this magnitude is attained by carefully balancing the line and associated equipment and by keeping inductive coupling with adjacent circuits down to a minimum.

The gain of a single repeater is limited to about 20 db. in order to keep cross-talk (induced signals) between different lines, which may be running parallel or in the same cable, down to the non-interfering background level. This cross-talk is most pronounced at points just outside the repeater stations where, as can be seen from Fig. 10 there is a difference of 20 db. in level between east and west-bound traffic. Under these conditions it will be seen that repeaters should be located at those points along the line where the signal has dropped to 20 db. below the normal level. The output of standard repeaters is normally set at the so-called "zero level" which, from the point of view of the telephone transmission engineer, corresponds to a current of two milliamperes fed into a 600 ohm line; that is to say, a power of 2.4 milliwatts.† This means, of course, that the signals enter

* A special transformer having 3 windings each with a center terminal so arranged that the signal feeds only in the direction of transmission.

† This level is used by telephone engineers and should not be confused with the levels of 6 and 10 milliwatts used in sound and broadcast calculations.

the repeater at an average level of —20 db. and that efforts should be made to keep the level of background interference down to between —30 and —45 db., depending upon the service for which the line is used.

POWER LEVEL INDICATOR

From the foregoing it is evident that means should be available for monitoring the transmission level at any point in the system as well as at the point of dispatch and reception. If allowed to fall too low at any point, the background noises in the system would be large in proportion to the signal. Then when the signal was stepped up in a repeater, the noise would also be amplified. On the other hand, a too high level might tend to overload the repeaters and they would distort the signals. For the purpose of monitoring, some form of A.C. voltmeter would

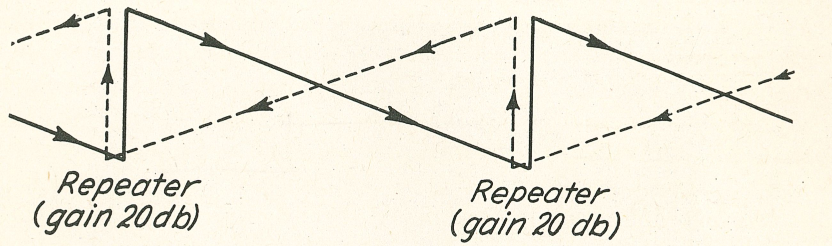


Fig. 10

be suitable, since the voltage across the line is a measure of the power, which is calculated from the formula:

$$P = E^2 / Z_o \qquad (6)$$

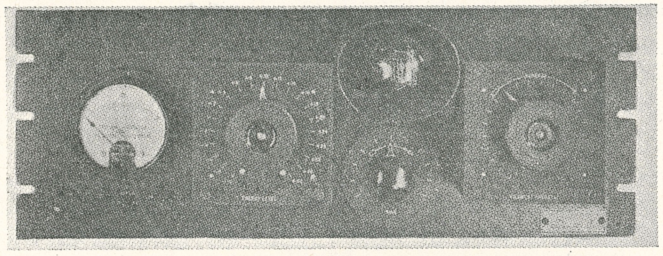
wherein the surge impedance Z_o remains constant. The scale of such a voltmeter can, of course, be calibrated in decibel steps with respect to some particular reference zero level.

In the transmission of speech or music the actual level varies from moment to moment over a considerable range and frequently at a rapid rate. The transmission monitor is interested primarily in the average power level from moment to moment. To obtain an average effective level, the voltmeter used should have its needle carefully damped, so that it will be sluggish and will not follow the rapid, erratic audio variations, but rather will show the more gradual fluctuations in the average level.

The type of voltmeter used for this purpose should obviously not consume too great an amount of power. This means that its impedance must be large compared with that of the line.

The range of levels to be measured frequently exceeds that which can be accurately observed upon a single scale voltmeter. To increase the range, the voltmeter may be preceded by a calibrated attenuator, such as we studied in a previous lesson.

The ordinary electrodynamometer type of A.C. voltmeter is not suitable for use as a power level indicator in an A.F. circuit since such a meter consumes altogether too much energy. The vacuum tube voltmeter, which consumes no power, can, of course, be used for this purpose. An ordinary calibrated potentiometer, whose total impedance is large compared with that of the line, may be used as a multiplier for extending the range of a vacuum tube voltmeter. These voltmeters often employ an input transformer, the secondary of which is tapped for variations in its range.



Volume Indicator

The new oxide rectifier voltmeter, however, combines a sufficient sensitivity with a large impedance so that it is entirely suitable for use as a level indicator. The advantage of this type of meter is that it does away with the difficulty of operating and maintaining a voltmeter of the vacuum tube type.

Instead of using a simple potentiometer for a multiplier with this rectifier type of meter it is best to employ a calibrated L-type attenuator which will present a constant impedance across the line.

Power level indicators are now available which combine a suitably damped oxide rectifier meter with a calibrated constant impedance attenuator and which have an operating range of about 50 db. The impedance of this instrument is made about 10 times the surge impedance of the line so that the power consumed by it is negligible. The instrument is calibrated in decibels for a definite line impedance. If used upon a line of dif-

ferent impedance, a correction constant must be applied. This too was studied in a previous lesson.

The design of all power level indicators should be such that variation in frequency up to 10 kilocycles will not affect the accuracy of the readings appreciably.

TRANSMISSION EFFICIENCY

The problem of transmitting signals from a generator to a load with the maximum efficiency is, of course, important and deserves our careful consideration. This problem should be considered under two headings; transmission over short lines and transmission over long lines.

A short line may be defined as one in which the actual resistance of the line is negligible compared with the impedance of both generator and load. Such a short line may be represented

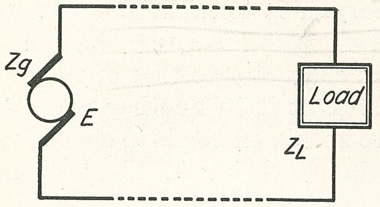


Fig. 11

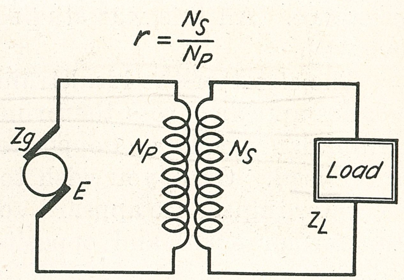


Fig. 12

as in Fig. 11, wherein a generator having a voltage E and an impedance Z_g is joined by a short line to a load having an impedance Z_L.

There are two ways in which the maximum transmission efficiency may be attained. Where the generator and load are both resistances the problem is simple, in fact, we studied this before. Where the load and source have reactance as well as resistance, matching is more difficult.

The most direct method of obtaining maximum signal transmission in this case consists of matching the impedances of the generator and load, directly, that is, making the reactive load equal to the reactance of the generator and opposite in character. That is, if one is a capacity, make the other an inductance. Thus X_C is balanced out by X_L. Then only resistance remains in the circuit and we know that maximum power is delivered when the load resistance equals the generator resistance.

The second method, for the case where Z_g and Z_L cannot be made equal and opposite in character, consists of inserting between the generator and load an "ideal" matching transformer having a secondary to primary ratio determined from the formula:

$$r = \frac{Z_L}{Z_g} \qquad (7)$$

where r is the ratio of secondary to primary turns and Z_L and Z_g represent the impedance values of the load and the generator, respectively. See Fig. 12.

An "ideal" transformer is defined as one in which there are no resistance losses and in which there is perfect coupling between primary and secondary windings. The ideal transformer may be approximated in practice by making the reactance of the primary and secondary considerably larger than their ohmic resistance. All this was studied in detail before and should be reviewed.

The effect of the ideal transformer is to make the load impedance appear across the primary of the ideal transformer as an impedance equal and opposite in character to that of the generator load. Or if you wish to look at it in another way, the generator impedance appears, so to speak, on the load side of the transformer equal and opposite in character to the load impedance.

Whether the load and generator are matched directly or indirectly through an ideal transformer, the maximum power supplied to the load is given by the equation:

$$P_L\,(\max) = \frac{E_g^2}{4R_g} \qquad (8)$$

In the case of a long line which has a certain surge impedance, Z_O, maximum transmission efficiency is obtained when the generator, line and load impedances are matched together directly by making each impedance equal, one feeding into the next impedance of opposite character, that is, $Z_g = Z_O = Z_L$. In the case where Z_g, Z_O and Z_L are all different values (see Fig. 13) they may be matched indirectly by inserting ideal transformers between generator and line and line and load.

Any actual transformer used for the purpose of impedance matching is not ideal and must, therefore, introduce a certain amount of loss into the transmission system; that is, a certain portion of the electrical energy will be transformed into heat

within the transformer, due to the I^2R losses in the wire, the eddy current and the hysteresis losses in the core. In the case of a properly designed transformer these losses will, however, be relatively small and they may be neglected. It should be realized that the designer of any transmission system cannot afford to use cheap or inefficient coupling devices.

IMPEDANCE CHANGING PADS

Instead of using transformers to match the impedances of two parts of a transmission system, it is sometimes the practice to employ an impedance changing resistance network or "pad." This device was taken up in a previous text. It has the desirable characteristic of being unaffected by frequency, and it is relatively inexpensive to manufacture. On the other hand the losses in such pads are generally much greater than in transformers and these losses must, of course, be compensated for by

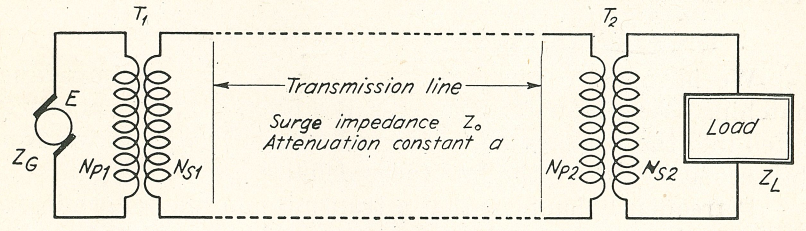


Fig. 13

additional amplification at some point in the system. Often an attenuation is desired along with the need for impedance matching and a fixed pad is employed. The loss in such a pad increases with the ratio of impedances to be matched.

LOCATION OF IMPEDANCE CHANGING DEVICES

It should be pointed out that a transmission line having a high impedance, especially if it is somewhat unbalanced in character, is more apt to pick up stray electric fields than a similar line of low impedance. Therefore, to minimize such interference, high impedance circuits should be reduced to the shortest possible length or "exposure," by using shielded transmission cable. It follows, too, that any impedance reducing device should be located as close as possible to the device having the higher impedance. The application of this principle is to be seen in the following cases:

A condenser type of microphone has a very high impedance.

It would, therefore, be undesirable to join it through a cable, even a few feet long, to an amplifier unit. To overcome this difficulty, one or more stages of amplification are built into the same unit which houses the microphone so that the high impedance circuit is very short and may be well shielded. The output impedance of this amplifier (several thousand ohms) is then stepped down to a few hundred ohms to pass into the cable joining the microphone unit to the main amplifier in the main control room where the impedance is stepped up again before the voltage is fed into the amplifier. The cable with its exposure to pick-up is, therefore, at low impedance.

A similar situation exists in the talking picture projection booth. The photocell is a very high impedance device and is therefore built into the "sound head" which contains also the photocell amplifier. The output impedance of this amplifier is stepped down to a low impedance (between 50 and several hundred ohms) and the signal is then carried to the main amplifiers.

AMPLIFIER INPUT TRANSFORMERS

We have been considering so far the need of impedance matching power transformers, so-called because electrical energy is fed into the primary and electrical energy is withdrawn from the secondary where the line faces definite impedances.

It frequently happens that a transmission line is terminated in a transformer which feeds into the grid of an amplifier tube. Such a transformer is known as an input transformer and is radically different in its characteristics from the impedance matching type of transformer since no appreciable energy is withdrawn from the secondary (except possibly at high frequencies). This is true because the grid circuit of the tube, biased negatively, presents nearly an infinite impedance to the transformer whose sole purpose is to supply a fluctuating signal voltage to the grid and cathode of the tube.

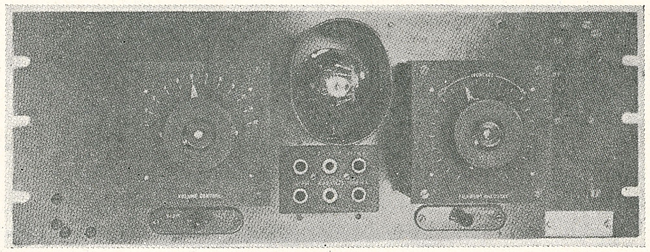
In such a case, it may be considered that the primary winding of the transformer is the load on the line. In order to obtain a maximum voltage across the primary, the reactance of this winding (the primary impedance), at the lowest frequency used should be made considerably larger than the impedance of the generator for a short line or the surge impedance of a long line.

Another method which insures better matching but which introduces somewhat greater losses is to close the line with a pure resistance equal to the surge impedance and to shunt the same with a transformer having a much higher primary impedance. In still another method a suitable matching transformer with a high step-up ratio is used. The secondary is closed by a high resistance which, if desired, may be used as a *gain control potentiometer* on the grid of the tube.

MONITORING

The process of controlling the energy level at any point in a transmission system, or of varying the relative levels from each of a number of generators fed into a single transmission system, is known technically as monitoring. The component parts of a monitoring system comprise some or all of the following:

1. Volume level indicators.
2. Gain controls for the amplifiers.
3. Suitable mixer panels (adjustable resistance networks).



Monitoring Amplifier

4. A monitor speaker is frequently desirable to enable the operator to hear what is being fed into the system.
5. Suitable jack or switching arrangements whereby the monitoring equipment may be inserted at any desired point in the system, or whereby various generator channels may be connected or removed.
6. Suitable signalling systems, usually in the form of signal lights, for communicating between the monitoring booth and the recording or broadcasting studios or with the stage or set in motion picture recording.

It is, of course, important that the monitoring equipment shall not in any way detract from the transmitted signals. This means that the gain controls must properly match the lines and associated equipment, and that the measuring devices (volume level indicators, etc.) shall present a high impedance to the transmission line and, furthermore, that if a monitoring speaker is used, it should, in general, be preceded by its own amplifier

so that no appreciable amount of power shall be withdrawn from the line.

The post of monitor is an extremely important one, calling for a thorough knowledge of the transmission system and a good judgment of acoustic values. An inattentive or incompetent operator at this "nerve center" of the transmission system may

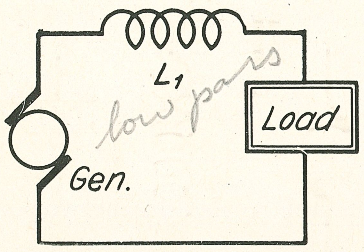


FIG. 14

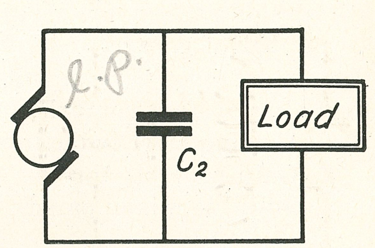


FIG. 15

easily ruin what would otherwise be an artistic and effective recording or broadcast program.

ELECTRICAL FILTERS

The complex electrical currents corresponding to sound waves of speech or music contain, at any one time, a large number of audio frequency components. For the purposes of analy-

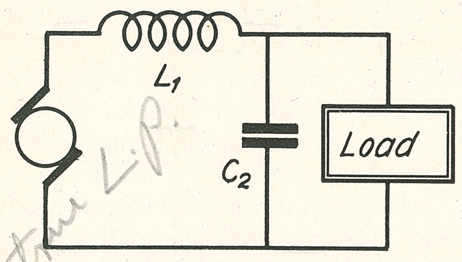


FIG. 16

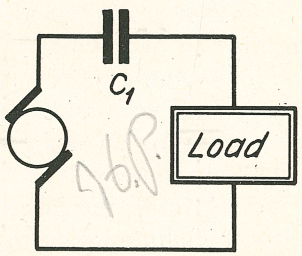


FIG. 17

sis and study, the communication engineer frequently desires to separate the various frequency components into groups, and to do this, he makes use of particular circuit arrangements known as electric wave filters. You are familiar with simple filter circuits from your study of resonant circuits and filters of the "brute force" type used in power supply devices to filter out hum. In carrier current transmission, telephony or telegraphy,

it is desired to separate frequencies of definite bands and again electric wave filters are used. Such filters may be classified into four groups.

1. *Low-pass filters,* which allow the lower frequency components to pass through them, at the same time reducing or cutting out the higher frequency components.

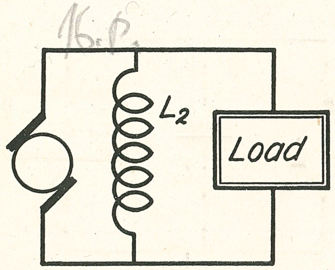


FIG. 18

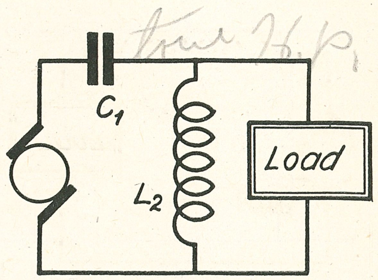
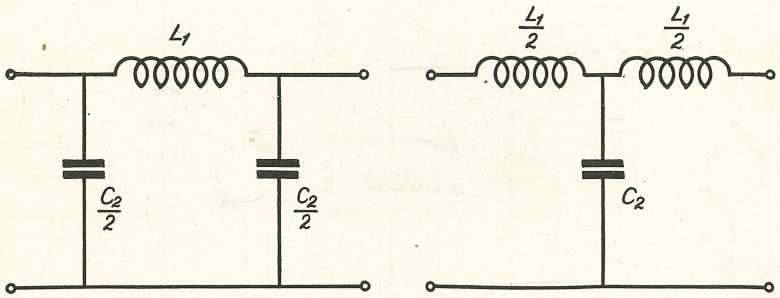


FIG. 19

2. *High-pass filters,* which allow the higher frequency components to pass through them, at the same time reducing or cutting out the lower frequency components.

3. *Band-pass filters,* which allow a certain intermediate range of frequencies to pass through them, while cutting out all frequencies above or below this range.



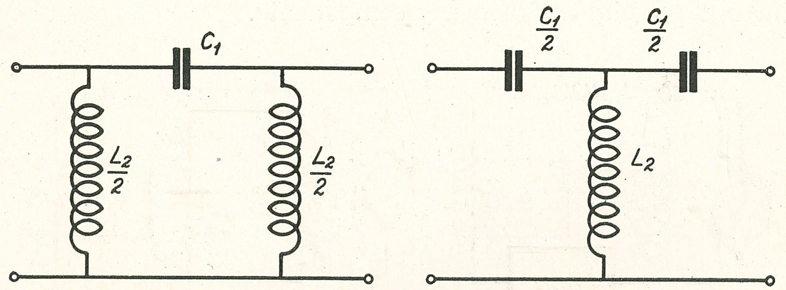
a FIG. 20 b

4. *Band elimination filters,* which cut out a certain intermediate range of frequencies but allow frequencies above or below this range to pass through them.

A detailed study of electric wave filters, like transmission line phenomena, involves very intricate mathematical processes. In this lesson we can only give fundamental concepts of the problems associated with their use and operation.

LOW-PASS FILTERS

If a generator is connected to a load by means of a line containing a series inductive element, as in Fig. 14, the latter acts in the manner of a low-pass filter since the impedance of the inductive element increases with the frequency.



a Fig. 21 b

Likewise, if the generator is connected to a load by a line having a shunt capacity element across it (Fig. 15) the latter behaves as a low-pass filter since its shunt impedance decreases as the frequency increases.

In either case, the attenuation of the filter increases with the frequency and there is no sharp line of demarkation between the passed and attenuated

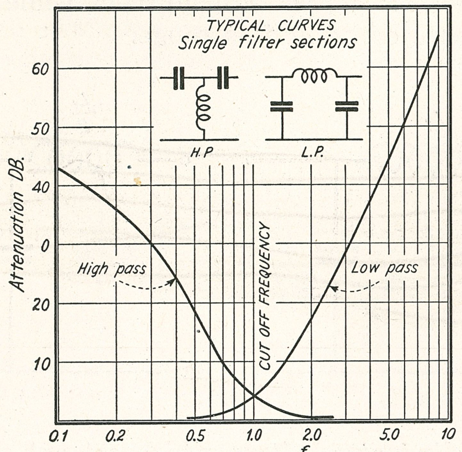


Fig. 22

ranges. This means that the attenuation is zero at zero frequency (direct current) while the transmission to the load is zero at an infinitely high frequency.

If, however, we combine the two cases mentioned, that is, employ both a series inductive element L_1 and a shunt capacitive element C_2, connected as in Fig. 16, we have a true low-pass filter which will show a more or less sharp

demarkation between the passed and attenuated portion at a particular frequency designated as the "cut-off" frequency* (see Fig. 22), whose value is determined by the equation:

$$F_o = \frac{0.3183}{\sqrt{L_1C_2}} \qquad (9)$$

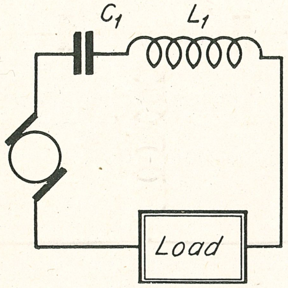


Fig. 23

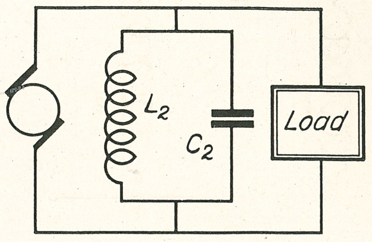
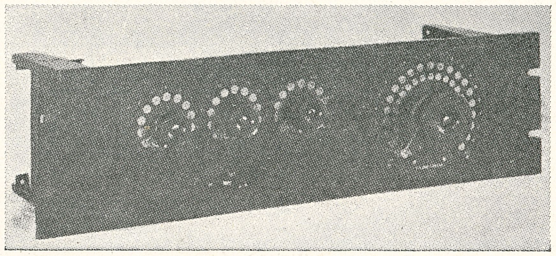


Fig. 24

In this and the following equations the values of inductance L_1 are in henries, the capacity C_2 in farads, and the frequency is in cycles per second.

The ordinary transmission line, since it contains series inductance and shunt capacity, is in effect a low-pass filter. The cut-off values for the type of overland transmission lines previously described will be seen to be about 58,000 cycles† per second for the open wire circuits and 37,000 cycles per second for



Line Compensating Unit

the No. 19 gauge cable. These values are seen to be much higher than voice frequencies so that the lines themselves when carrying only voice frequency currents give no appreciable selective filter action, the attenuation being due to resistance and leakage losses alone.

* A wave filter also has a surge impedance determined from the formula: $Z_o = \sqrt{L_1/C_2}$ Filters inserted in lines must have the same surge impedance as the line to avoid reflection losses.

† Z_o = 540 ohms: L_1 = .00298 henries; C_2 = .01022 microfarads.

HIGH-PASS FILTERS

If a generator is connected to a load by a series capacitive element, the latter acts as a high-pass filter since its impedance decreases as the frequency increases (see Fig. 17).

Likewise, if a generator is connected to a load by a line having a shunt inductive element as in Fig. 18, the latter behaves as a high-pass filter since the shunt impedance increases with the frequency. In either of these cases, considered separately, the attenuation of the high-pass filter decreases progresively as the frequency increases, there being no abrupt line of demarcation between the attenuated and the passed ranges. This means that the transmission to the load will be zero at zero frequency (direct current) while the attenuation will be zero at an infinitely high frequency. If, however, we employ both a series capacitive and a shunt inductive element, C_1 and L_2, we will have a true high-pass filter (see Fig. 19) which will show a more or less sharp demarkation (see Fig. 22) between the attenuated and passed ranges occurring at the cut-off frequency given by the equation,

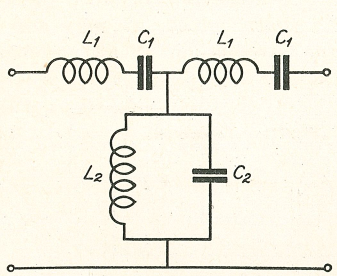


Fig. 25

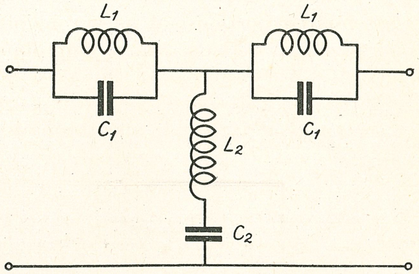


Fig. 26

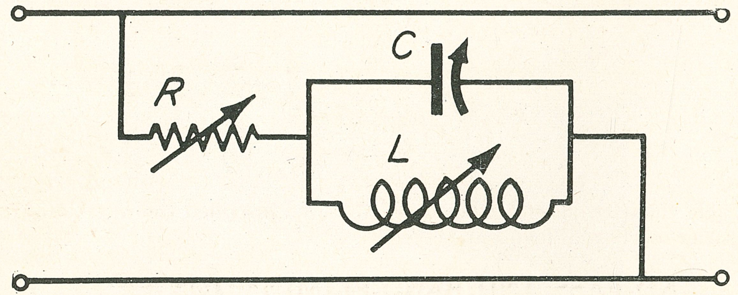


Fig. 27

$$F_o = \frac{0.07958}{\sqrt{L_1 C_2}} \qquad (10)$$

Low-pass and high-pass filters are usually assembled in symmetrical sections of the T type or π type as indicated in Figs. 20 and 21.*

* The surge impedance in this case is: $Z_o = \sqrt{\frac{L_2}{C_1}}$

CASCADING LOW AND HIGH-PASS FILTERS

A single section of low or high-pass filter has a definite attenuation characteristic. A curve showing the attenuation of the filter plotted against frequency or against the ratio of frequency to the theoretical cut-off value is shown for a typical case in Fig. 22. The sharpness of the cut-off depends primarily upon the Q-factor of the inductive unit, the cut-off being more sharp as Q increases. "Q" is the ratio of the reactance of the unit to its alternating current resistance.* If we desire to obtain a sharp demarkation between passed and attenuated portions, or as we might say a sharp cut-off, we may add a second identical section which will double the attenuation at off resonant frequencies. For example, if the db. attenuation for a high-pass filter at one-half the theoretical cut-off is 18 db. (see Fig. 22), the cascading of another filter section would provide an attenuation of 36 db. Likewise, three sections will triple the attenuation value to 54 db., etc., provided the filter impedances match the source and load impedances.

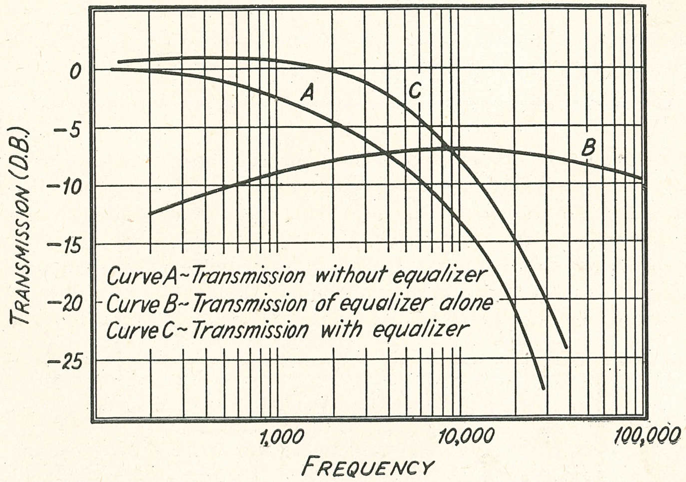


Fig. 28

BAND-PASS AND BAND-ELIMINATION FILTERS

Suppose we desire to pass a relatively wide band of frequencies between values of f_1 and f_2, f_2 being higher than f_1. It is obvious that we could accomplish this by employing a low-pass filter section with a cut-off value set at f_2 connected in series with a high-pass section having a cut-off set at f_1. Two sections, working together, will then pass a band between f_1 and f_2 provided the surge impedances are equal.

Another type of band-pass filter, intended to pass a relatively narrow band, makes use of resonant and anti-resonant (parallel resonant) circuits. A con-

* This Q-factor you already know is very important if selectivity is desired in an R.F. coupling or resonance coil.

denser and inductive element both connected in series with the line (see Fig. 23) have a minimum impedance at resonant frequency.

At frequencies above or below resonant frequency, the reactive component of the impedance causes a progressively increasing attenuation of the signals transmitted. The curve would be like any series resonance curve.

If an inductive and capacitive element are connected together in parallel across the line, as in Fig. 24, at resonant frequency the shunt impedance of this anti-resonant circuit becomes a maximum value.

It is common practice to construct a resonant band-pass filter having two series resonant circuits and one shunt anti-resonant circuit giving the familiar symmetrical T type of network shown in Fig. 25. The two branches resonate at a common frequency, the average frequency of the band to be passed. If both the resonant and anti-resonant branches resonate at the same frequency a sharp acceptance characteristic will be obtained. If each of the three branches is made to resonate slightly off the mean frequency, a band-pass action will result.

It is sometimes desired to eliminate a single frequency or narrow band of frequencies using for the purpose a band elimination filter. It is not practicable

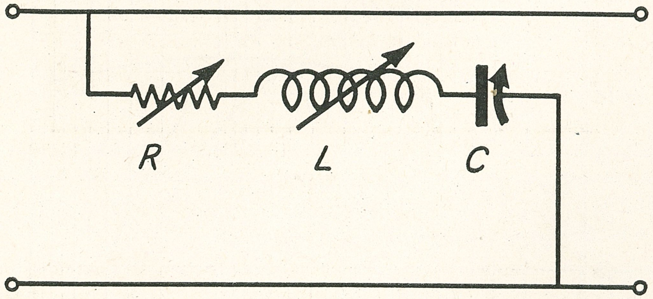


Fig. 29

to construct such a filter from separate high-pass and low-pass sections but a resonant T section filter of the type shown in Fig. 26 comprising series anti-resonant circuits and a shunt resonant circuit may be used.

A wave filter has an input and output terminal impedance, and if the filter is made symmetrical they will be equal. We might call this impedance the characteristic or surge impedance of the filter. If such a device is to be inserted into a line the Z_0 of the filter must equal the Z_0 of the line, otherwise serious losses and distortion may result.

EQUALIZERS

It frequently happens in practice that a generating device, such as a microphone or a phonograph pickup unit, feeds, through a transmission line, a load such as a sound recording device or a loudspeaker. Such a system may have a characteristic at the load end which is not sufficiently uniform over the audio frequency band to provide the desired fidelity. This deficiency may sometimes be corrected, wholly or in part, by employing an electrical network known as an equalizer.*

* Equalizers are used wherever fidelity characteristics need improving. When used to correct line distortion, they are referred to as line equalizers.

Consider the specific case in which the frequency-transmission characteristic falls off too rapidly in the upper end of the audio frequency region. A circuit arrangement, as shown in Fig. 27, when connected across a transmission line, offers a maximum shunting impedance and hence tends to produce a peak in the transmission frequency characteristic at that particular frequency for which the resonance equation around the *L-C* loop holds true. If, now, we increase

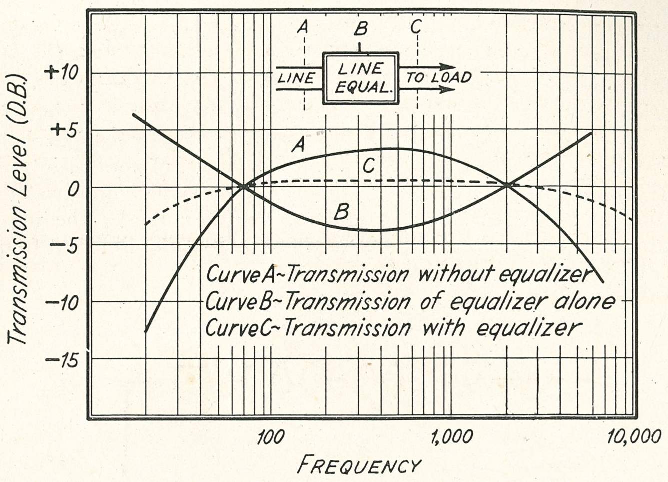


Fig. 30

the value of the resistance, *R*, the resonant peak becomes flattened and less pronounced. By setting this resonant frequency at a value somewhat above the upper end of the desired working range and adjusting the magnitude of the resistance, it is possible to give the equalizer such a rising characteristic in the upper working range that, combined with the falling characteristic of the circuit,

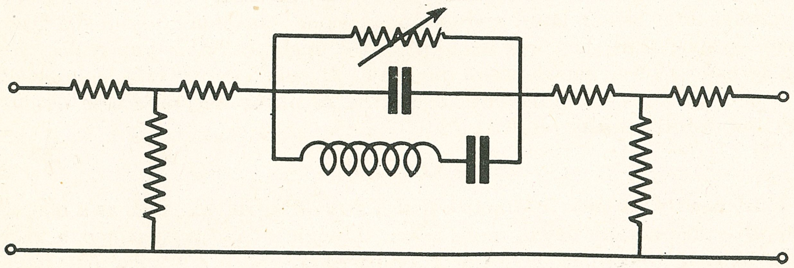


Fig. 31

a net result is obtained which maintains its level to a higher frequency. This is clearly indicated in Fig. 28.

Equalizers having fixed characteristics are used to correct definite faults, while variable equalizers, having both an adjustable *L-C* circuit and an adjustable *R*, are made for meeting any variation in transmission characteristics

which may occur. Such equalizers are sometimes tuned at a mid-range or low-range frequency to compensate for some deficiency in the system. An equalizer of this sort is, in effect, a very broad band-pass filter having an adjustable band-pass frequency and an adjustable sharpness of peak.

In a similar manner, an equalizer may be arranged as shown in Fig. 29. This, of course, represents a band elimination filter and may be used to flatten out some particular and objectionable resonance peak in the system, as is indicated in Fig. 30.

Special equalizers of more complicated types are sometimes used for a specific purpose, a typical example being shown in Fig. 31. The impedance of an equalizing network varies, in general, with the frequency. In order that this variation may not have too great an effect upon the transmission of a wide frequency range, the equalizer circuit is frequently "protected" on both sides by resistive pads, as indicated in Fig. 31. Such pads, of course, introduce an additional amount of attenuation which may have to be compensated for by amplification at some point in the system, but they render the impedance, looking into the equalizer from either side, more uniform for different frequencies and hence they are frequently used.

TEST QUESTIONS

Number your answer sheet ~~11C~~ 6CA and add your *student number*.

Never hold up one set of lesson answers until you have another set ready to send in. Send each lesson in by itself before you start on the next lesson.

In that way, we shall be able to work together much more closely, you'll get more out of your Course, and the best possible lesson service.

1. What characteristic of a non-reactive line makes it ideal for audio frequency current transmission?
2. If you measured the terminal impedance of a 40 mile transmission line, at the source end, with the load end open and closed, how would the two measurements compare?
3. What is done to prevent reflection losses at the source and load ends of a transmission line?
4. If a wave filter is inserted in a line, what precautions must be observed to prevent loss?
5. Why is it customary practice to reduce a source impedance to a low value, even though the line may be only several hundred feet long?
6. How can a wave filter system be designed for sharp cut-off?
7. Draw a schematic diagram of a conventional "pie" type high-pass filter.
8. Why are equalizers used in audio frequency circuits?
9. What is a band elimination filter?
10. What two devices are used for impedance matching purposes in transmission lines?